

Evaluation of operating conditions on DBFC (direct borohydride fuel cell) performance with PtRu anode catalyst by response surface method



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ABSTRACT

Borohydride has been considered as a potential fuel for the fuel cell application due to its high energy density. A DBFC (direct borohydride fuel cell) is an electrochemical device that converts chemical energy stored in borohydride and oxidant directly to electrical energy as long as the fuel and oxidant is supplied. One of the main problems encountered in a DBFC is the simultaneous hydrolysis of BH_4^- at the anode surface. The hydrolysis decreases the fuel utilization and fuel cell performance, since hydrogen bubbles hinder the contact of catalyst with reactant. This study investigates the effect of operating conditions (cell temperature, borohydride concentration, flow rates of fuel and oxidant) on DBFC performance by RSM (response surface methodology). PtRu/C is used as the anode catalyst to systematically investigate the effect of hydrogen evolution rate on the fuel cell performance. The maximum power density is obtained at 80 °C fuel cell temperature, 0.5 M NaBH_4 concentration, 5 $\text{cm}^3 \text{min}^{-1}$ flow of anolyte and 100 $\text{cm}^3 \text{min}^{-1}$ flow of oxygen.

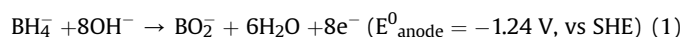
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1. Introduction

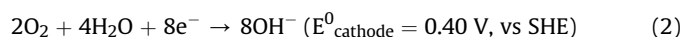
In recent years, there has been a considerable interest in a direct borohydride fuel cell (DBFC) due to its high theoretical cell voltage and power density [1,2]. DBFCs are good candidates for portable and mobile applications since they eliminate hydrogen storage problems and can be used safely due to liquid fuel usage. Sodium borohydride (NaBH_4) is a well known, stable and non-toxic reducing agent. It is the most attractive material due to its high energy density (9.3 Wh g^{-1}), its ability is not only to release $8e^-$ per borohydride ion at a low electrode potential but also to generate a high power output per unit fuel quantity [1]. In a DBFC, NaBH_4 solution is directly fed to the anode part of the fuel cell as a fuel. DBFC employs oxygen, air or hydrogen peroxide as an oxidant in the cathode part. The only byproduct is non-toxic sodium metaborate (NaBO_2), which can be converted to NaBH_4 easily without any pollution.

The reaction at the anode part of the DBFC is the oxidation of the borohydride ion, BH_4^- to metaborate (BO_2^-) and water according to

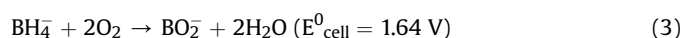
Eq. (1). This reaction should take place in strongly alkaline media ($\text{pH} > 12$), since BH_4^- is unstable in acidic or neutral environment.



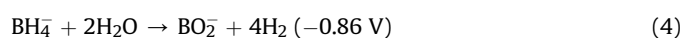
Reaction at the cathode part of the DBFC is the reduction of oxygen or air according to Eq. (2).



The overall reaction is written as:



One of the main problems encountered in a DBFC is the simultaneous hydrolysis of BH_4^- at the anode surface according to the reaction in Eq. (4).



Hydrogen gas evolved during the hydrolysis reaction decreases the anodic potential. Hence, the fuel efficiency is decreased. Moreover, it causes problems in mass transport and system design [1–3]. Hydrogen bubbles aggregate easily between the anode

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Table 1
Design table of the experiments.

Run	Factor 1 cell temperature, °C	Factor 2 borohydride concentration, M	Factor 3 anode flow rate, cm ³ min ⁻¹	Factor 4 cathode flow rate, cm ³ min ⁻¹
1	80	1.5	5.0	400
2	50	1.5	1.0	400
3	80	0.5	5.0	100
4	50	0.5	1.0	100
5	80	1.5	1.0	100
6	50	1.5	5.0	100
7	50	0.5	5.0	400
8	80	0.5	1.0	400

electrode and membrane, thus, due to reduced fuel contact, productivity of borohydride oxidation falls. In addition, it causes increased ohmic resistance by blocking the ion transfer through the membrane [4]. Also, evolved hydrogen via hydrolysis blocks the channels in the flow field, and then decreases the fuel cell performance. Depending on the catalyst composition and operating conditions, the borohydride oxidation pathway can change between Eq. (3) and Eq. (4). There are many research studies reported on DBFC electrocatalysts that try to reduce the hydrolysis of BH_4^- and yield high cell performance [5–9].

The performance of a DBFC can also be increased by the optimization of the operating conditions [7,10]. In literature, there are several studies investigating the performance of fuel cells. Carton and Olabi reported the parameters that affect the performance of a PEMFC (proton exchange membrane fuel cell) [11]. Chen et al. discussed the impacts of some operating conditions such as the operating temperature, input gas compositions and operating pressure on the performance of the molten carbonate fuel cell-stirling heat engine hybrid system [12]. Taymaz et al. applied RSM (response surface methodology) to optimize the effects of operating conditions on a DMFC (direct methanol fuel cell) [13]. Silva and Rouboa optimized the DMFC operating conditions using RSM [14]. The semi-empirical model introduced in this research are consistent with the models provided by Yang et al., where a systematic approach to model the relationships between the operating parameters and the direct methanol fuel cell performance was introduced [15]. Anis et al. studied the optimization of direct 2-propanol fuel cell performance using statistical design of experiments approach [16]. Thepkaw et al. determined the key

parameters of the active layer of PEMFC using full factorial design [17]. Boyacı San et al. analyzed the polymer composite bipolar plate properties on the performance of PEMFC by RSM [18]. Fofana et al. recently investigated multilayer electrode preparation on PEMFC performance [19].

RSM has been widely used in engineering design optimization studies. It was developed by Box and collaborators in the 50s. RSM is a collection of mathematical and statistical techniques based on the fit of polynomial equation to the experimental data. It can be used to define the relationships between the response (output variable) and the independent variables (input variables), alone or in combination in the processes. In addition to analyzing the effects of the independent variables on the response, it generates a mathematical model. The objective is to simultaneously optimize the levels of variables to achieve the best performance. The main advantage of using response surfaces is that, obtaining of the variable relationship and model is extremely rapid. Relatively few data sets are required to build a model relating inputs and output variables. The application of RSM reduces the cost of expensive analysis methods and their associated time and volumes of numerical data analysis. RSM can be used successfully in different disciplines such as chemical and biochemical processes, energy and production engineering [20,21].

The aim of this study is to analyze the DBFC operating conditions by a statistical approach. In this study, PtRu/C as the anode catalyst and Pt/C as the cathode catalyst in DBFC are used and the behavior of the hydrolysis of NaBH_4 (Eq. (4)) is investigated by the operating conditions. Although Ru is known as a hydrolysis catalyst, PtRu/C is used as the anode catalyst to simulate the aggressive hydrogen

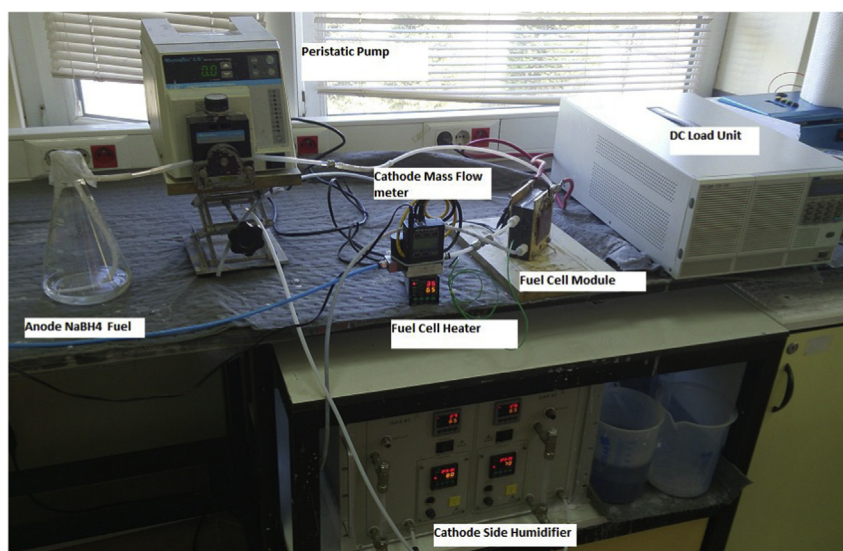


Fig. 1. The photo of the experimental set up.

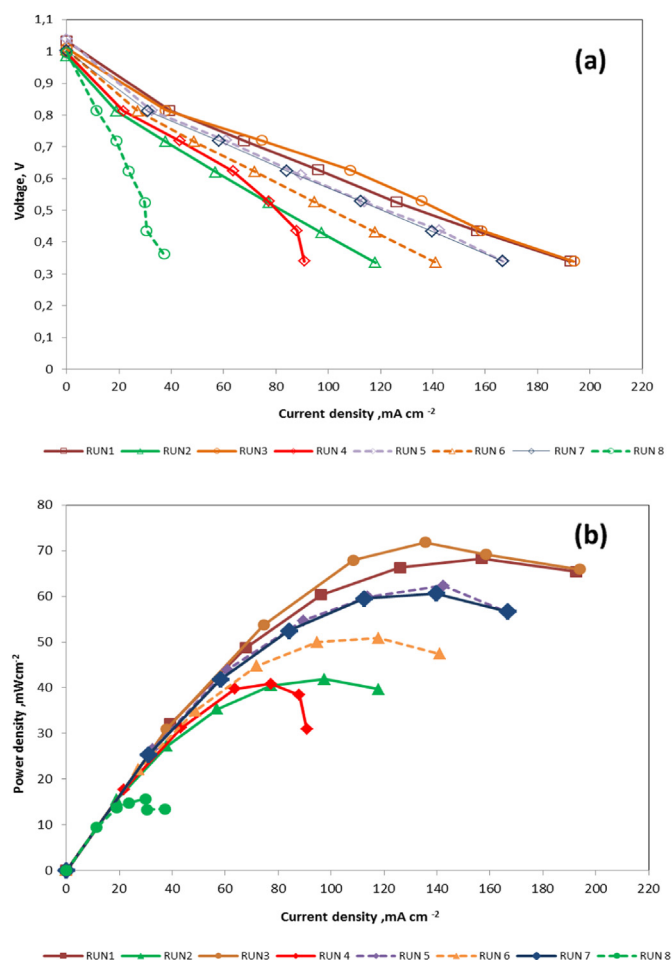


Fig. 2. Cell voltage (a) and power density (b) curves at catalyst loadings of 0.44 mg cm^{-2} for different runs.

evolution conditions. The critical operating conditions on the DBFC performance are investigated in the presence of PtRu/C anode catalyst as different common DBFC literature. The effects of cell temperature, borohydride concentration, flow rates of fuel and oxidant on the performance of DBFCs are analyzed by RSM and a predicting model has been proposed. The model has been compared with the numerous data obtained by a lot of experiments performed varying the parameters one at a time. The effect of the critical parameters on the performance of DBFC is determined

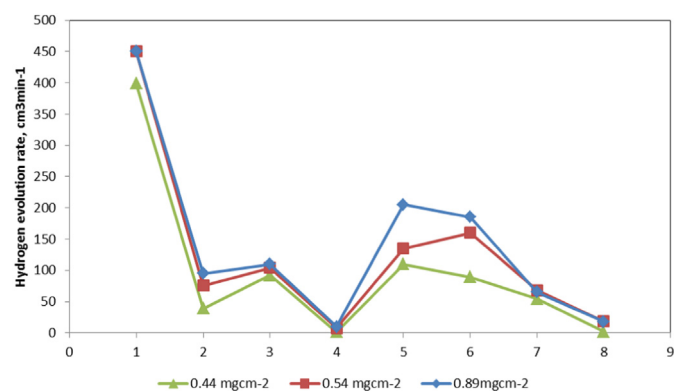


Fig. 4. The comparisons of hydrogen evolution for different runs.

experimentally. Thus, the paper is quite original and provides contribution to science and technology.

2. Experimental

2.1. Materials and chemicals

The chemical reagents, including 2-propanol, NaOH, NaBH₄, and 5 wt.% Nafion solution (Sigma–Aldrich), Nafion 117 membrane (DuPont, USA), 20 wt.% Pt/C on Vulcan XC-72 carbon support (BASF Fuel Cell, Inc.) are all purchased. Homemade 60 wt.% PtRu/C electrocatalyst was used in the electrode preparation.

2.2. Experimental design

There are four input factors for two levels. For a 2^4 design with a single replicate, 16 MEAs have to be produced with 16 runs. In this study, one half factorial design, 2^{4-1} is selected which requires only 8 runs. The construction of the design is shown in Table 1 by considering the 2^{4-1} design with four parameters (cell temperature, borohydride concentration, anode and cathode flow rates).

2.3. Fuel cell performance tests

The anode electrocatalyst ink was prepared by mixing 2-propanol with 5 wt.% Nafion solution and 60 wt.% PtRu/C. Then, the ink was coated on a carbon cloth (Electrochem, Inc.), yielding a metal loading mass on the electrode of 0.89 mg cm^{-2} . The Nafion 117 membrane was cleaned by boiling in 3 wt.% H₂O₂ for 1 h, followed by boiling in ultrapure water for 2 h. The cleaned membrane was activated in 2 M NaOH solution for 1 h prior to use. The anode/membrane/cathode unit was compressed between two graphite

Table 2

ANOVA results for power density at 0.89 mg cm^{-2} catalyst loading.

Source	Sum of squares	DF	Mean square	F value	p Value
Model	2851.85	6	475.31	144.96	0.0137
A	123.89	1	123.89	11.72	0.1809
B	125.39	1	125.39	11.86	0.0499
C	1307.94	1	1307.94	123.73	0.0571
D	352.79	1	352.79	33.37	0.1091
AC	210.13	1	210.13	19.88	0.0405
AD	731.71	1	731.71	69.22	0.0476
Std. dev.	3251			R ²	0.996
Mean	66.448			Adj R ²	0.974
C.V.	4893			Pred R ²	0.764
Press	676.537			Adeq precision	22.435

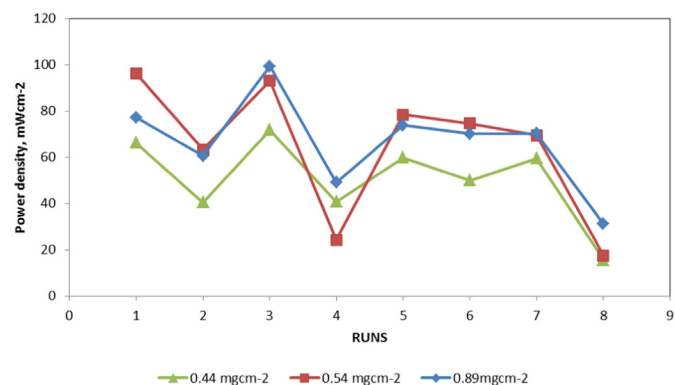


Fig. 3. The comparisons of the power density at 0.5 V.

Table 3
ANOVA results for hydrogen evolution rate at 0.89 mg cm⁻² catalyst loading.

Source	Sum of squares	DF	Mean square	F value	p Value
Model	15,0936.4	4	37,734.1	9.44286	0.0477
A	26,381.05	1	26,381.05	6.601789	0.0825
B	76,323.25	1	76,323.25	19.0997	0.0222
C	32,691.25	1	32,691.25	8.1809	0.0646
AB	15,540.85	1	15,540.85	3.889057	0.1432
Std. dev.	63.21			R ²	0.926
Mean	155.83			Adj R ²	0.828
C.V.	40.57			Pred R ²	0.777
Press	85,248.96			Adeq precision	8765

blocks with pin type flow fields. Silicon gaskets were assembled between the electrodes and the graphite blocks. The active area of the fuel cell was 25 cm². Cell performance was tested against a 1 mg cm⁻² Pt/C cathode coated on a carbon paper. Peristaltic pumps were used to feed the fresh analyte (an aqueous solution of 1 M NaBH₄ and 6 M NaOH) at a 3 cm³ min⁻¹ flow rate. The oxidant fed to the cathode chamber. The oxidant was humidified by passing through a bubbler at 65 °C. The temperature is controlled using heating pad and heating band in stack and lines of reactants, respectively. Cell performance data were obtained using an electrochemical fuel cell test system (Electrochem 400 W) and a computer controlled E-load system (ECL 150). The photo of experimental set up is given in Fig. 1.

3. Results and discussion

A comparative investigation of DBFC polarization behavior is carried out with respect to the effect of cell temperature, borohydride concentration, flow rates of fuel and oxidant. The higher and lower level values are used in a statistical analysis to determine significant parameters and can be seen in Table 1.

3.1. Effect of catalyst loading

The pathway of the borohydride oxidation changes depending on the catalyst type and operating conditions. The hydrolysis reaction is easily activated by high temperature, NaBH₄/NaOH ratio, and a catalyst such as Ru, Ni and Co. The hydrogen evolution by borohydride hydrolysis reaction forms two phases in anode side and hinders the interaction of the active side and the reactant. In

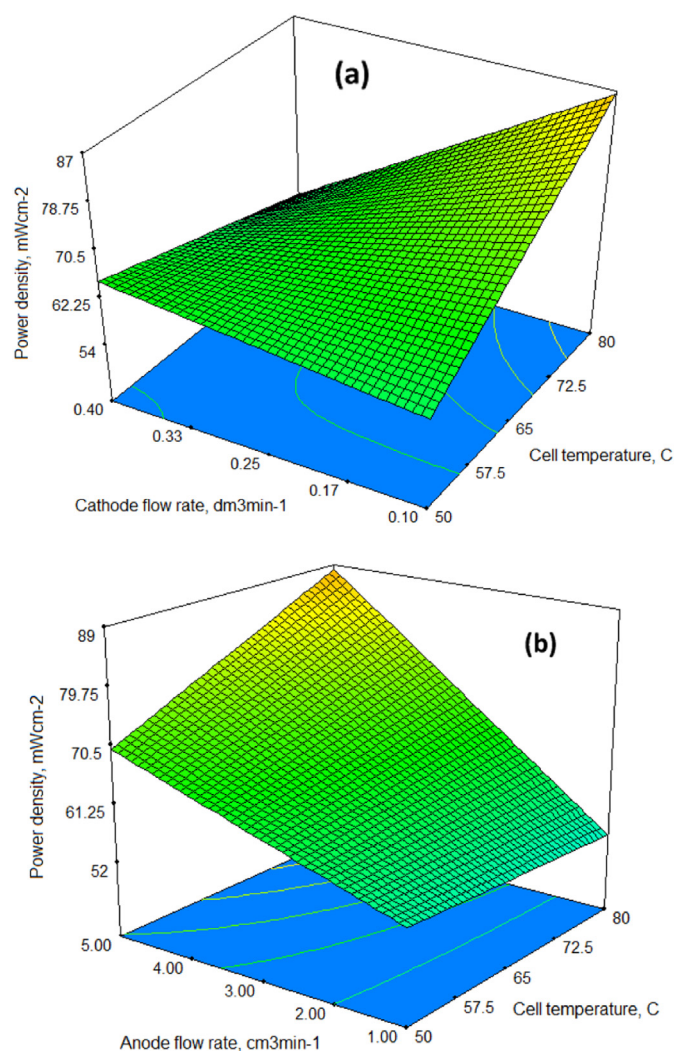


Fig. 6. Power density as a function of cathode flow rate and cell temperature (a), anode flow rate and cell temperature (b).

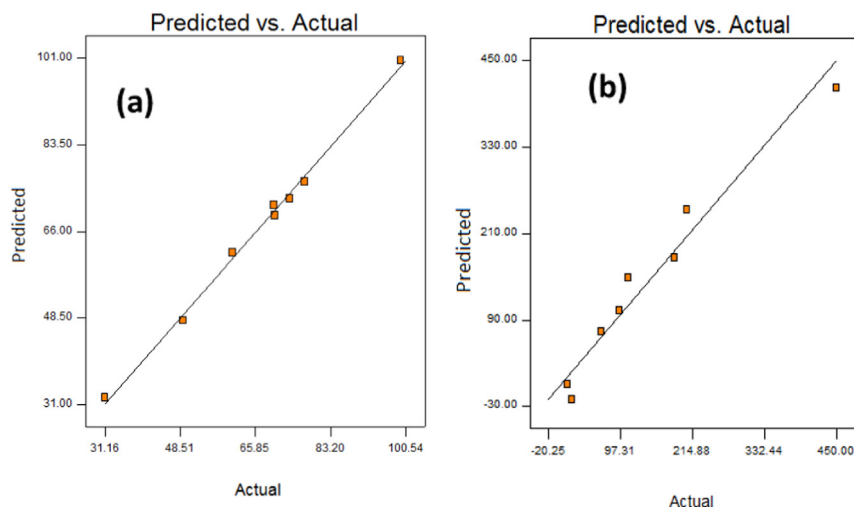


Fig. 5. The actual response data versus the predicted data for power density (a) and hydrogen evolution rate (b).

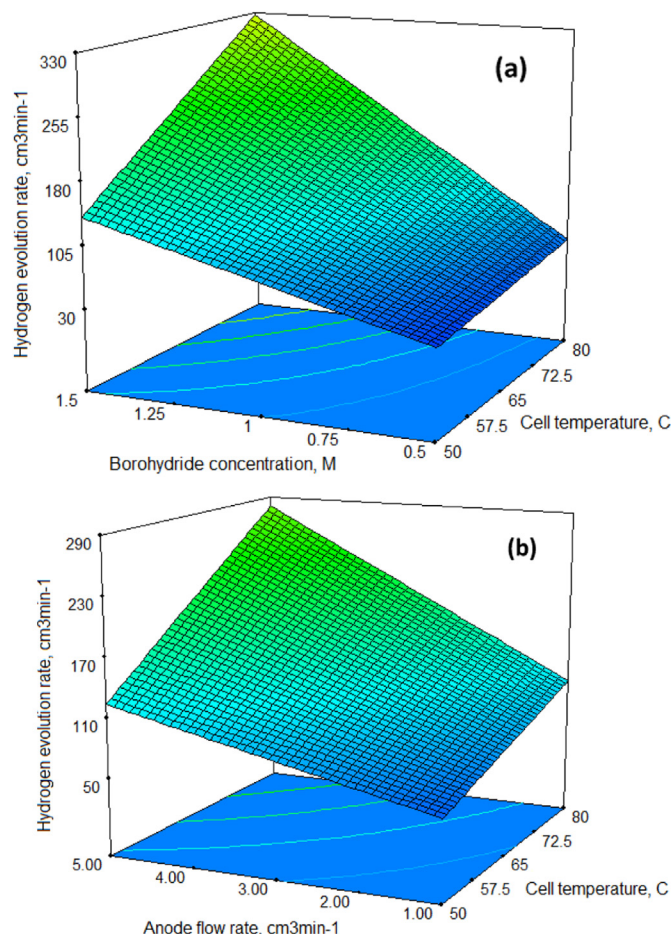


Fig. 7. Hydrogen evolution rate as a function of borohydride concentration and cell temperature (a), anode flow rate and cell temperature (b).

this study, the effects of the cell temperature, borohydride concentration, flow rates of fuel and oxidant on the direct borohydride fuel cell oxidation and the hydrogen evolution are investigated at carbon supported PtRu catalyst by using a statistical approach. In addition, the effect of the catalyst loading is investigated to determine the contribution of the process parameter on the fuel cell performance. Eight runs are carried out at low and high values of process parameters for the three catalyst loadings (0.44 , 0.54 , 0.89 mg cm^{-2}). Mainly similar performance trends are observed for all loadings. But the highest fuel cell performance is obtained at 0.89 mg cm^{-2} . The fuel cell performance drastically increases with the increase in the anode flow rate (Fig. 2). The comparisons of the power density at 0.5 V and the hydrogen evolution with respect to

different catalyst loadings are given in Figs. 3 and 4. According to the results, the higher power density values are obtained for Run 3, Run 1, Run 5, Run 6 and Run 7. Nevertheless, Run 1 has a maximum hydrogen evolution rate due to the higher values of the process parameters. Run 3, carried out at a maximum cell temperature and the anode flow rate, has lower hydrogen evolution rate than Run 5 and Run 6. The interesting results are observed for Run 3, Run 7 and Run 1. The conditions of Run 3 and Run 7 change the reaction towards to the direct oxidation of sodium borohydride (Eq. (3)), but the hydrolysis reaction (Eq. (4)) is dominant for Run 1 conditions. Since the highest fuel cell performance is obtained at 0.89 mg cm^{-2} , the statistical analysis is performed by using experimental data for this catalyst loading. The data were analyzed using DESIGN EXPERT software to find the effect of each factor on the output response. ANOVA results of power density and hydrogen evolution rate according to analysis of the cell temperature, borohydride concentration, anode and cathode flow rate at 0.89 mg cm^{-2} catalyst loading are given in Tables 2 and 3, respectively (A : Cell temperature, B : Borohydride concentration, C : Anode flow rate, D : Cathode flow rate). In mathematical equation estimation, Design Expert tool is used and an equation is achieved. For coefficient estimate, regression coefficient representing the expected change in response y per unit change in x when all remaining factors are held constant. In orthogonal designs, it equals one half the factorial effects. SYSTAT program and Gauss Elimination method is used for equitation coefficient calculation and correlation. Coefficients values are nearly same for two programs. So we conclude that our mathematical formula is correct and reliable.

The targets in the analysis are to obtain a maximum value of adjusted R^2 and to get a lower value of the difference between adjusted R^2 and predicted R^2 than 0.3 . Value of adequate precision measures the signal to noise ratio. The ratio of 22.435 indicates an adequate signal, since the ratio greater than 4 is desirable. The significance of the quadratic model equation is expressed with the coefficient of determination R^2 , F and p values. F value (144.96) implies that the model is significant. The p value less than 0.0500 indicate model terms are significant where the values greater than 0.1000 indicate that the model terms are insignificant. In this case, B (borohydride concentration), C (anode flow rate), AC (temperature*anode flow rate) and AD (temperature*cathode low rate) are significant model terms. Since the design expert software checks the model hierarchies containing two factor interactions before running an ANOVA, the interaction terms (AC and AD) are considered as significant. A well formulated model should include all main effects and their interactions. Thus, A and D are also used in our model although they are seemingly insignificant. The relationship between the response and the input is given in Eq. (5).

$$\text{Power density} = -2.39277 + 0.81248 * \text{Cell temperature} + 7.91807 * \text{Borohydride concentration} - 4.71107 * \text{Anode flow rate} + 232.01356 * \text{Cathode}$$

Table 4
Contribution list of power density and hydrogen evolution rate.

Term	For 0.89 mg cm^{-2} catalyst loading		For air		For top to bottom fuel flow	
	% Contribution for power	% Contribution for hydrogen	% Contribution for power	% Contribution for hydrogen	% Contribution for power	% Contribution for hydrogen
A	4.38	16.05	24.39	11.82	5.10	5.63
B	4.33	46.95	11.87	33.38	24.68	37.48
C	45.70	20.36	0.39	31.97	38.17	42.77
D	12.32	1.22	4.47	3.38	24.35	0.54
AB	0.37	9.09	36.50	5.93	0.07	0.2
AC	7.34	3.23	1.02	5.35	2.6E-3	3.5
AD	25.56	3.10	21.36	8.17	7.62	9.88

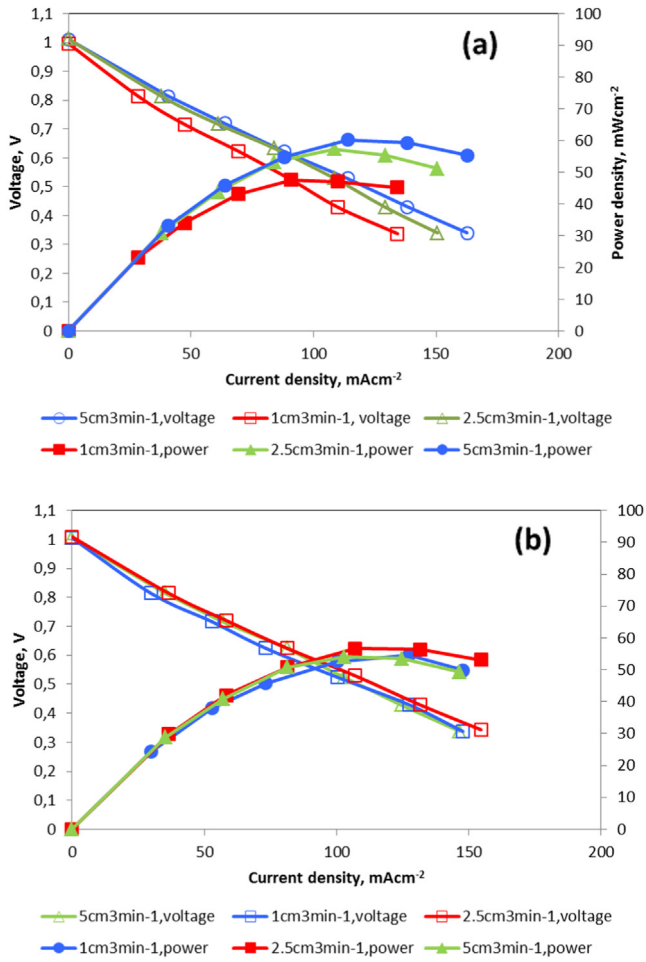


Fig. 8. The effect of the anode flow rate on the fuel cell performance at 50 °C (a) and 80 °C (b).

$$\text{flow rate} + 0.17084 * \text{Cell temperature} * \text{Anode flow rate} - 4.25053 * \text{Cell temperature} * \text{Cathode flow rate} \quad (5)$$

As seen in Eq. (5), the most effective parameters on power density are borohydride concentration and cathode flow rate. Also interactions of cell temperature with anode and cathode flow rates are seen in equation.

The model F value of 9.44286 for the hydrogen evolution rate implies the model is significant. Also the p value of 0.04777 is less

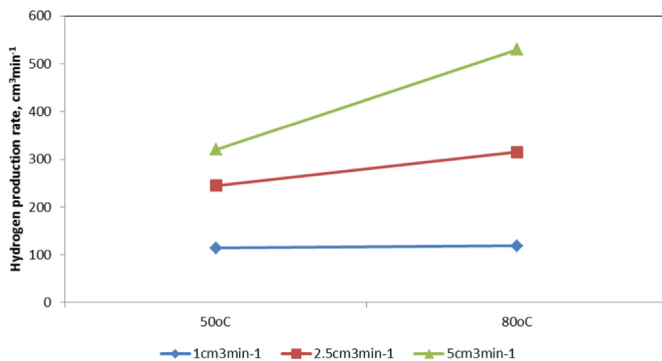


Fig. 9. The effect of the anode flow rate on the hydrogen evolution rate.

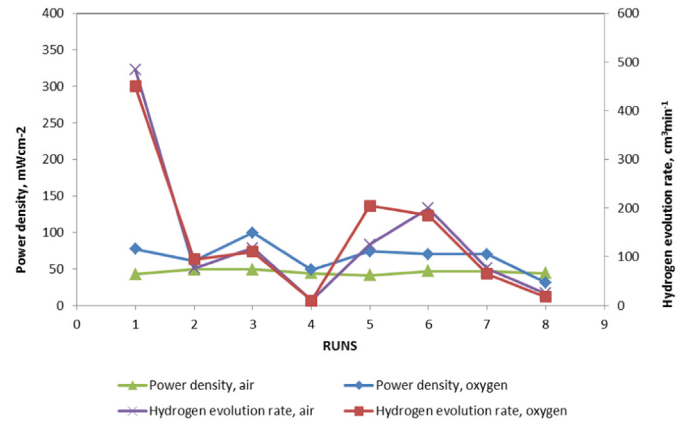


Fig. 10. The effects of oxidant type on the fuel cell performance and the hydrogen production rate for different runs.

than 0.005. Values greater than 0.1 indicate the model terms are not significant.

Fig. 5a and b shows the plots of the actual power density and hydrogen evolution rate data versus the predicted power density and hydrogen evolution rate data, respectively. The figures confirm that the predicted data of the response from the models are in

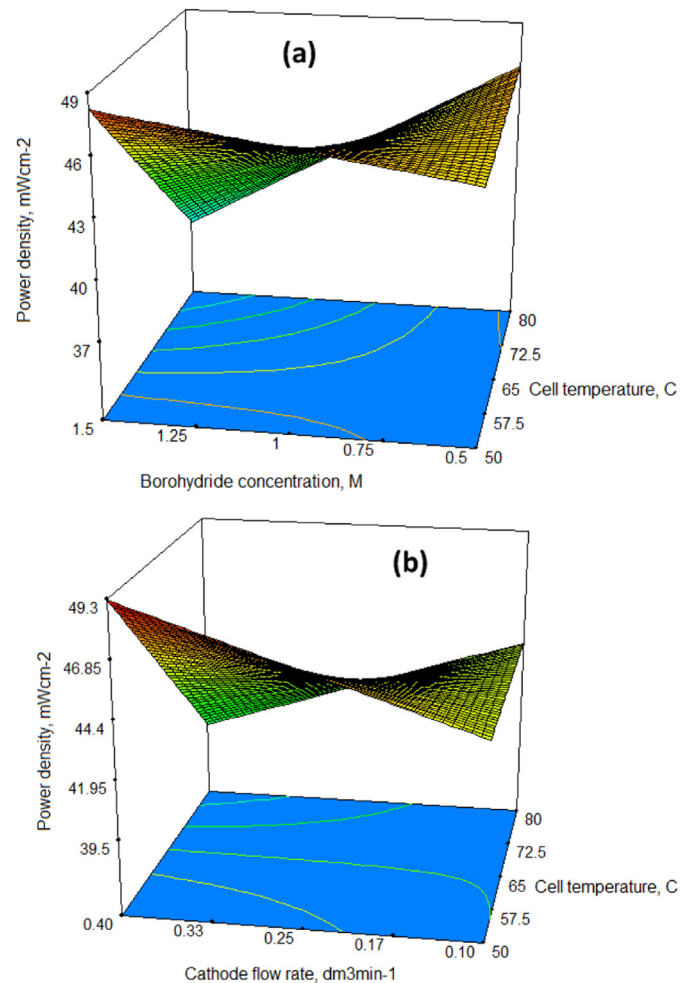


Fig. 11. Power density as a function of borohydride concentration and cell temperature (a), cathode flow rate and cell temperature (b).

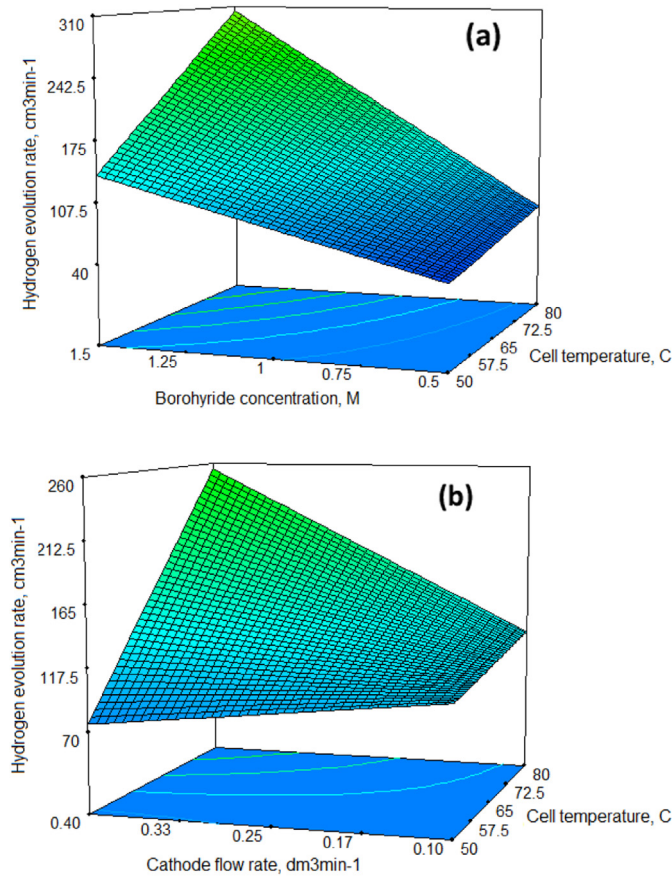


Fig. 12. Hydrogen evolution rate as a function of borohydride concentration and cell temperature (a), cathode flow rate and cell temperature (b).

agreement with actual response data. Also, according to the high R^2 (0.996) and adjusted R^2 (0.974) values for power density and the high R^2 (0.926) and adjusted R^2 (0.828) values for hydrogen evolution rate; the models fit the experimental data (Tables 2 and 3). The results indicate that our semi-empirical model is effective for predicting the DBFC performance.

$$\text{Hydrogen evolution rate} = -2.27083 - 2.04833 * \text{Cell temperature} - 186.63333 * \text{Borohydride concentration} + 31.96250 * \text{Anode flow rate} + 5.87667 * \text{Cell temperature} * \text{Borohydride concentration} \quad (6)$$

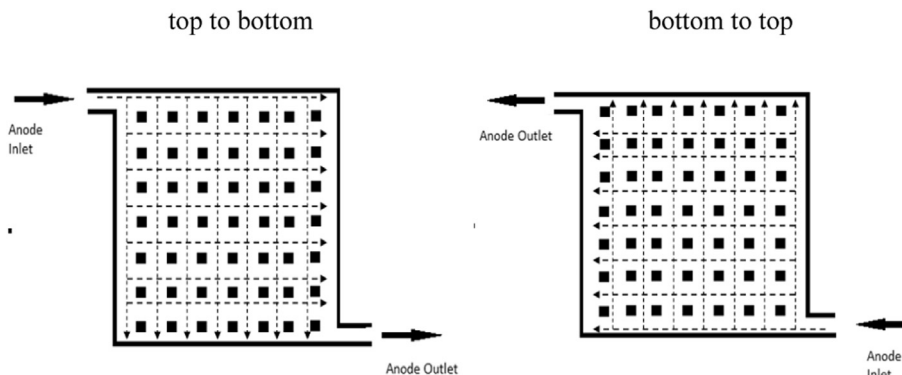


Fig. 13. The schematic illustration of the anode flow directions on the flow field.

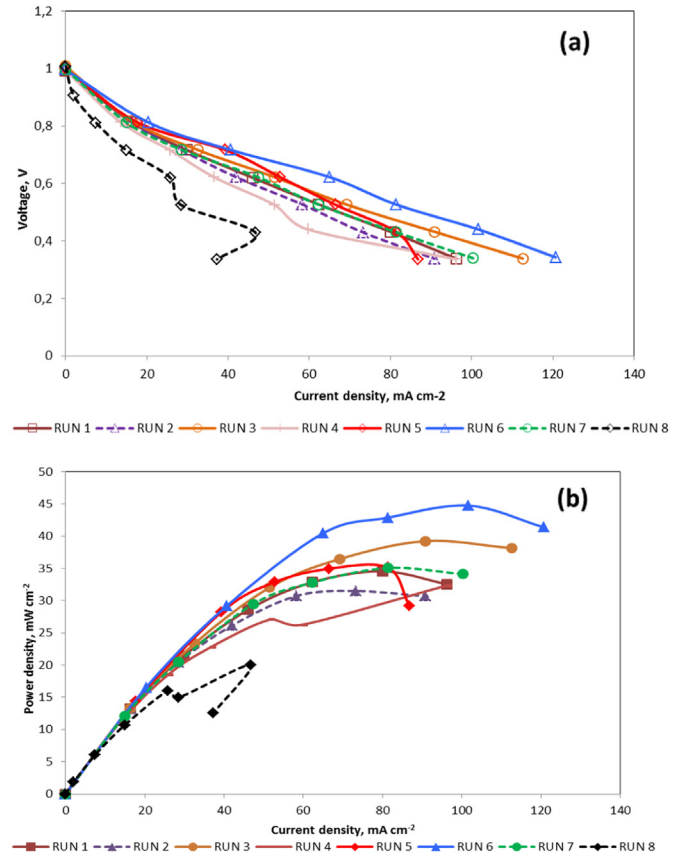


Fig. 14. The effect of the anode flow direction from top to bottom on the fuel cell performance: cell voltage curve (a) power density curve (b).

The effects of the factors on the response are shown in Figs. 6 and 7. The factors in Figs. 6 and 7 are selected according to the percentage of contribution in Table 4. At the low cathode flow rate, the power density sharply increases with the cell temperature (Fig. 6a), due to the enhancement in oxidation kinetics of borohydride with high temperature. However, the power density decreases with increasing temperature at a high cathode flow rate, because of the dehydration at the cathode part with high flow rate and high temperature. The small increase of the power density with increasing the cathode flow rate is observed at low temperature. The highest power density is obtained at high temperature and anode flow rate as seen in Fig. 6b. At the higher anode flow rate, hydrogen is removed easily and mass transfer limitation decreases.

Besides, the BH_4^- mobility increases at the high temperature. According to Fig. 6a and b results, cell temperature and anode flow rate are the dominant parameters on fuel cell performance.

The statistical analysis is also used to evaluate the effect of the process parameters on the hydrolysis reaction. In Fig. 7a and b, the effects of the borohydride concentration, anode flow rate and cell temperature on the hydrogen evolution rate are shown. The hydrogen evolution rate increases with increasing cell temperature, borohydride concentration and anode flow rate. The cathode flow rate is the least effective parameter on the hydrogen evolution rate. According to the result, the borohydride oxidation and hydrolysis reactions are affected similarly with cell temperature and anode flow rate. Run 3, which is carried out in cell temperature of 80 °C, borohydride concentration of 0.5 M, anode flow rate of 5 $\text{cm}^3 \text{min}^{-1}$ and cathode flow rate of 100 $\text{cm}^3 \text{min}^{-1}$, has higher power density and lower hydrogen evolution rate than other runs. Our results are compatible with the expected behavior of DBFC [22].

3.2. The effect of the anode flow rate

Generally, the power density and the current density increase with increasing temperature due to improved mass transport of the reactants, faster kinetics of borohydride oxidation and increased ionic conductivity. On the other hand, the hydrolysis of the borohydride, the mass transport limitation due to the formation of

hydrogen on the anode surface and the dehydration of the membrane enhance at the high temperature [1]. The increase in the anode flow rate improves the cell performance due to the better mass transport and ease of the removal of the evolved hydrogen gas [23]. However, the ratio of the performance improvement depends on the type of flow field [11]. Since we used pin type flow field in our studies, the effect of the anode flow rate is especially important. On the other hand, the leakage of electrolyte, the pumping power, the stresses on the electrode materials and the sealing materials must be considered for high anode flow rate. The borohydride concentration is another factor that affects the DBFC performance. The increase in the borohydride concentration increases the mass transport and the borohydride crossover [1]. The reaction rates of oxidation and hydrolysis increase with increasing the reactant concentration. The surplus hydrogen in the anode side changes the effects of the other parameters. The cathode performance deteriorates due to the crossover of borohydride and the accumulation of NaOH solution. The accumulation prevents the mass transport of the oxygen in the cathode side.

To deeply investigate the effect of the temperature and anode flow rate, the anode flow rate is increased at minimum and maximum values of temperature with respect to statistical analysis. In Fig. 8a and b, the performance data belong to the anode flow rates are given at 50 °C and 80 °C, respectively. The power density increases with increasing anode flow rate at 50 °C (Fig. 8a), whereas

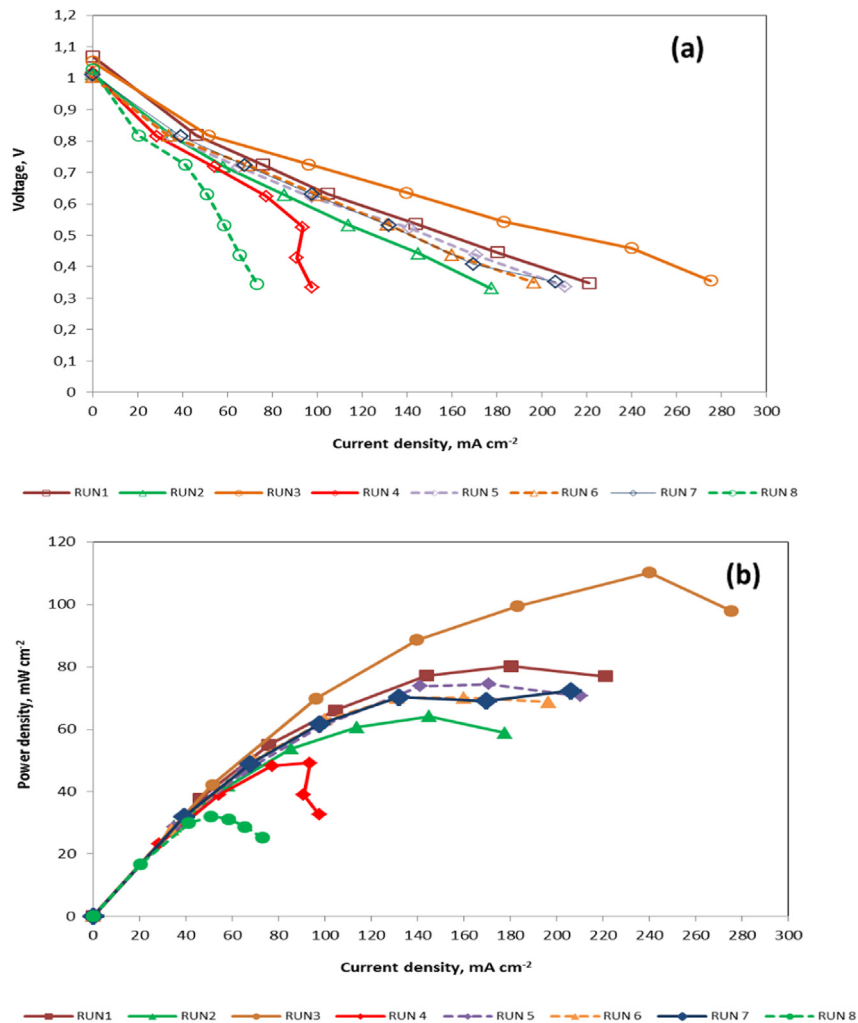


Fig. 15. The effect of the anode flow direction from bottom to top on the fuel cell performance: cell voltage curve (a) power density curve (b).

the cell performance firstly increases and then decreases with the anode flow rate at 80 °C (Fig. 8b). On the other hand, the hydrogen evolution rate increases with increasing anode flow rate for both temperatures (Fig. 9). The increase in the hydrogen evolution rate for high anode flow rate at 80 °C is higher than the lower anode flow rates. The results are compatible with the ones reported by Cheng and Scott in 2006 [24]. It is concluded that, the hydrogen evolution rate especially is affected with anode flow rate at high temperature.

3.3. The effect of the type of oxidant

The effect of the air on the performance of the DBFC is investigated. The eight runs are carried out at low and high values of process parameters with air as oxidant. The power density values for air and oxygen are between 35 mW cm⁻² to 48 mW cm⁻² and 20 mW cm⁻² to 110 mW cm⁻², respectively (Fig. 10). The highest power density is obtained for Run 3. The hydrogen evolution rates for Run 1, Run 5 and Run 6 are higher than that of other Runs. According to the results, Run 3 conditions (cell temperature of 80 °C, borohydride concentration of 0.5 M, anode flow rate of 5 cm³ min⁻¹ and cathode flow rate of 100 cm³ min⁻¹) are preferential for the borohydride oxidation. The conditions of Run 1 are dominant toward to hydrolysis reaction for oxygen and air. The statistical analysis is carried out to determine the contribution effect of the process parameters (Table 4). In Fig. 11a and b, the effects of the borohydride concentration and cell temperature and the effects of the cathode flow rate and cell temperature on the power density are shown, respectively. The power density of the fuel cell increases with increasing borohydride concentration and stack temperature at the low temperature and the low borohydride concentration. However, the lowest power density is obtained at high borohydride concentration and high cell temperature. The similar behavior is found for the effects of cathode flow rate and cell temperature on the power density of fuel cell. The lowest power density is obtained at high cathode flow rate and high cell temperature. On the other hand, the highest hydrogen evolution is obtained at the high values of the process conditions (Fig. 12a and b).

3.4. The effect of the anode flow direction

Serpentine, parallel and pin type flow channels are the most commonly used flow field designs for DBFC (direct borohydride fuel cell). A pin type channel is used in the anode side to eliminate the increasing of the pressure. On the other hand, the limited use of the active side for the pin type is possible because of the formed gas hydrogen. Therefore, the feeding direction for anode from bottom to top or from top to bottom is important. In this study, since the hydrogen is produced via hydrolysis reaction, the borohydride solution is fed from bottom to top of the fuel cell stack. Fig. 13 shows the schematic illustration of the anode flow directions on the flow field. The effect of the anode flow direction from the top to the bottom is shown in Fig. 14. The lower power density and current density data are obtained for top to bottom (Fig. 14) than bottom to top (Fig. 15). On the other hand, the highest power density is obtained for Run 6 carrying out at cell temperature of 50 °C, borohydride concentration of 1.5 M, anode flow rate of 5 cm³ min⁻¹ and cathode flow rate of 100 cm³ min⁻¹. The values of the power density are between 25 mW cm⁻² to 45 mW cm⁻². Fig. 16 shows the power density and hydrogen evolution rate for both directions. The power density data for the top flow close to each other. In addition, the higher hydrogen evolution rates are obtained for Run 1, Run 6 and Run 5. According to the results, the anode flow direction from bottom to top shows the best performance due to easy

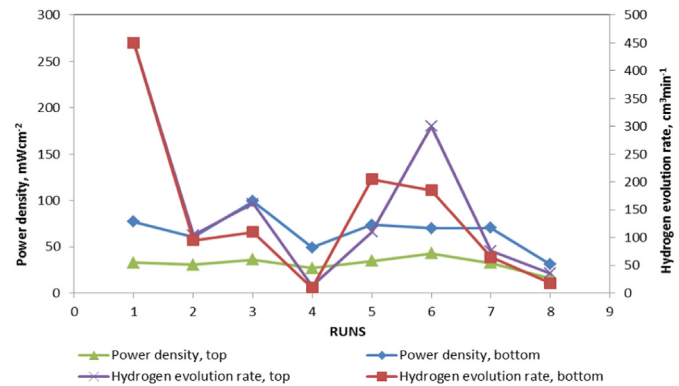


Fig. 16. The effects of the anode flow direction on the fuel cell performance and the hydrogen production rate for different runs.

removal of the hydrogen in the anode side. The analysis of the process parameters on the power density and hydrogen evolution rate are given in Fig. 17a and b. Fig. 17 is drawn according to the percentage of contribution in Table 4. An increase in power density

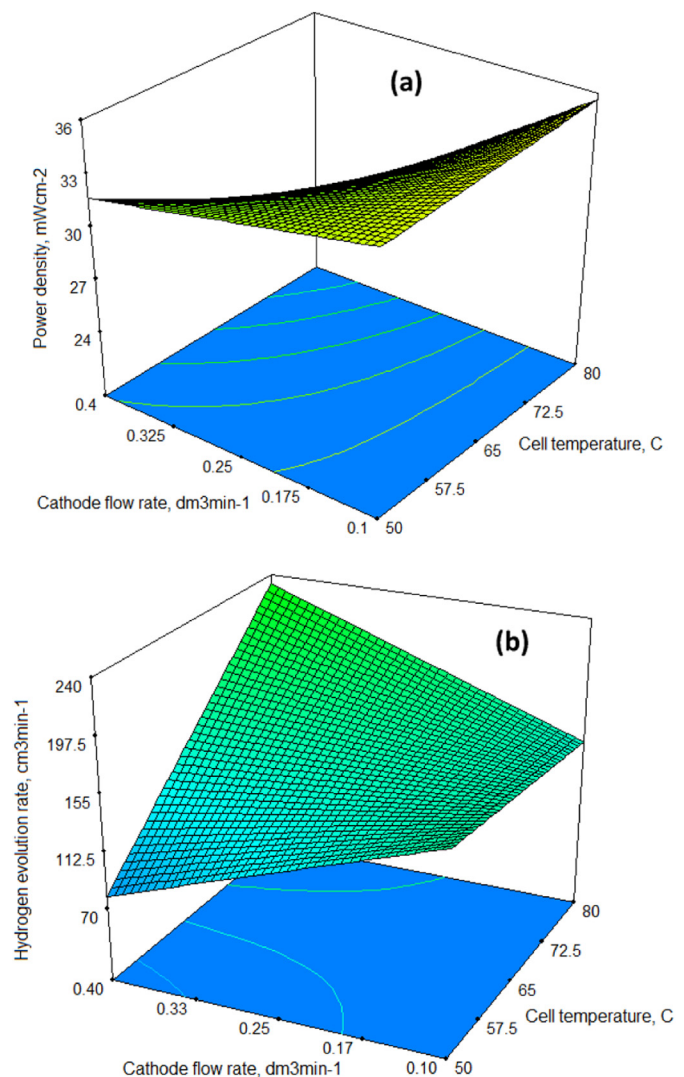


Fig. 17. Power density as a function of cathode flow rate and cell temperature (a), hydrogen evolution rate as a function of cathode flow rate and cell temperature (b).

is observed with an increase in the cell temperature and a decrease in the cathode flow rate (Fig. 17a). On the other hand, the lowest hydrogen evolution rate is obtained at low temperature and high cathode flow rate (Fig. 17b).

4. Conclusions

In this study, RSM is used to analyze the effects of cell temperature, borohydride concentration, anode and cathode flow rates on power density of DBFC and hydrogen evolution rate. Additionally, the effect of the PtRu/C anode catalyst loading on the oxidation and hydrolysis of borohydride is investigated. It is found out that, the power density and the hydrogen evolution rate are increased with increase in catalyst loading. Fuel cell power density and the hydrogen production rate are observed to increase with the increase in anode flow rate at high temperatures. On the other hand, due to the dehydration at the cathode part with high flow rate and high temperatures, power density decreases with increasing temperature at a high cathode flow rates.

Moreover, high temperature increases borohydride hydrolysis, crossover rate and mass transport of the reactants and ionic conductivities of the electrolyte. The performance enhancement is observed for bottom to top direction due to improved flow in anode side with pin type channel, having more uniform fuel distribution in cell by removing of hydrogen. Consequently, the higher temperature, borohydride concentration and flow rates of reactants enhance both the oxidation and hydrolysis reactions. The higher fuel cell performance is obtained with oxygen rather than air. On the other hand, different interactions are observed for oxygen (anode flow rate and cell temperature) and air (borohydride concentration and cell temperature). We concluded that the effects and the interactions of parameters can be different for minimum and maximum level of parameters. The maximum power density is obtained at 80 °C fuel cell temperature, 0.5 M NaBH₄ concentration, 5 cm³ min⁻¹ flow of anolyte and 100 cm³ min⁻¹ flow of oxygen.

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